Additive manufacturing: The power of powder

April 30, 2019

Originally published March 1, 2019

In the Sigma Complex at Los Alamos National Laboratory, John Carpenter—a materials scientist—sits quietly at his desk analyzing his latest data. Colorful line graphs and black-and-white images fill his computer screen. The glow of the images pulls him forward to investigate more closely, and he smiles at the success these data imply.

Since 2015, Carpenter has been a lead scientist for the NNSA–funded Pressure Vessel Project. Working with researchers at Sandia National Laboratories, Savannah River National Laboratory, Lawrence Livermore National Laboratory, and Kansas City National Security Campus, Carpenter guides this inter-laboratory collaboration.

This project is the first of its kind because it circumnavigates the linear "process leads to product" methodology to instead work with a chicken-or-egg scenario: What comes first, the manufacturing process or the product? For Carpenter, the answer is both. The initial process leads to a product, which is then analyzed to determine how that process can be improved, which leads to a better product, and so on. This is what Carpenter and the NNSA have termed science-based qualification, and it is at the crux of the Pressure Vessel Project's purpose: Use the scientific method to prove, step by step, that a process known as additive manufacturing (AM) is suitable for building metal components.

"We are pioneering the pathway for additive manufacturing," Carpenter explains, "and once this pathway is established for the pressure vessel, other metal components can be built."

Materials scientist John Carpenter is confident in the additive manufacturing pathway being forged by science-based qualification.

The point of the pressure vessel

The pressure vessel these scientists are making is a humble component no bigger than an average person's palm. Made from stainless steel powder, its simple egg-like structure belies this component's importance for national security—it is the model by which science-based qualification will be used to determine whether AM can reliably manufacture and repair metal components that are faced with extreme environmental conditions and are relevant to national security.

In particular, component repair is important for the aging U.S. nuclear stockpile. Over time, stockpile components suffer from age and need to be repaired or replaced, but often the knowledge and equipment for manufacturing those components have disappeared with time. People retire, machines break, and life moves on, which is why scientists such as Carpenter are exploring AM as the technology for filling in the gaps.

The AM process produces real-world products from powdered materials such as metals, polymers, and ceramics. AM is similar to 3D printing but with two key differences: the scale and the materials. In terms of scale, 3D printing is at one end (for everyday consumers) and AM is far at the other (industrial). The materials can be far more exotic in AM, and AM can build products that are far more useful as compared with 3D printing. For weapons, AM provides an alternative way to build, repair, or refurbish critical components.

Carpenter’s team is materializing a small army of pressure vessels from metal powder, with each new vessel slightly better than the one before. The army will continue to grow until NNSA requirements have been met and characteristics such as material strength and ductility, burst pressure, resistance to leakage, and performance in extreme environments are assessed.

The data from this latest pressure vessel are what splash Carpenter’s screen with color. Coming full circle—process to product and back to process again—these new data put proof behind the science-based qualification method.

Where additive manufacturing fits in

Different from traditional forms of manufacturing, such as molding and casting, AM is a solution for building uniquely challenging components, such as components with complex architectures. For example, nature’s intricately fashioned honeycomb is a structure that cannot be realized by traditional machining methods but can easily come to life using AM. This is one niche that AM can serve without completely replacing other manufacturing methods. “Additive manufacturing is not going to replace traditional machining, but it allows for the expansion of capabilities,” says Colt Montgomery, an AM postdoc at Sigma.

As of yet, there is no certification process for AM, but in the opinion of Michael Brand (an AM engineer at Sigma who has played a role in developing the technique from its beginning), a certification process is needed for the future. This is because the success of the technique is still somewhat dependent on the skill and experience of the operator and because AM technology changes rapidly over short amounts of time. “It has blown my mind how far additive manufacturing has gone in the five years since I started,” Brand says.

A

3D STL file, like the one shown here of a pressure vessel, is the starting point for additive manufacturing. STL stands for Standard Triangle Language.

How additive manufacturing works

Essentially, AM takes a 2D drawing and brings it to life as a 3D component. Computer software takes the first step in initiating this process by modeling a drawing out of tiny triangles. These triangles spread over the drawing to form a net-like 3D image—an STL file. From there, the file can be customized to add labels to the 3D component, insert holes, or delete portions.

The STL file encompasses all of the program instruction details required to physically build the component, but first the file must be sliced. For powder-bed AM (the type used in the Pressure Vessel Project), slicing software cuts the STL file into 40-micrometer horizontal layers; this is the thickness each physical layer will possess. Note that the diameter of a human hair is 60 micrometers and a single micrometer is a millionth of a meter, so these AM slices are quite thin. The sliced file is fed by a computer to the AM machine, communicating how to actually build the pressure vessel layer by layer.

In the Sigma Complex, the AM shop houses a single computer atop a modest desk, which is in stark contrast to the considerable AM machine that dominates the middle of the room. The rectangular 14-foot-long by 8-feet-tall by 5-feet-deep machine offers only a small window for viewing the “build” chamber, which is equipped with four infrared lasers. Brand explains that four lasers as compared to the traditional one laser reduces the component build time substantially (which is still on the order of 80–100 hours).

Carpenter’s AM team uses stainless steel powder between 20 and 60 micrometers in particle size, adding it to the argon-filled AM chamber one layer of powder at a time. Stainless steel is the material of choice for this project because it is relatively inexpensive, readily available, easy to work with, and well-characterized in terms of properties for non-AM applications. This allows Carpenter’s team to focus on the process variables at play rather than being surprised by an unexpected result due to a lesser-understood material.

Inside the argon-filled AM chamber, the first layer of stainless steel powder is spread on a build plate. The sliced STL file tells the laser where to strike in order to melt w powder together, according to what is needed for that layer of the pressure vessel. To an observer, the laser is invisible, until it strikes the metal and a bright spark of light appears. Not all of the powder in a given layer is melted, some remains loose.

Before another layer of powder is added on top of the first, the build plate moves down 40 micrometers (equal to the thickness of the layer that will be added). The pressure vessel is built from the bottom up and is constantly lowering deeper into the chamber below. After 4,000–5,000 layers, the finished component is below the starting place of the first layer and buried within the excess loose powder that wasn’t melted by the laser. Like an archaeologist excavating a bone, the component is carefully removed from the chamber using a vacuum and brushes.

Much of that excess powder can be recycled for the next build. Careful post-processing of the excess powder removes any particles that have been sintered (or glued) together because these particles would be difficult to spread while building the next pressure vessel.

A

partially manufactured pressure vessel.

The process–product feedback loop

At the crux of the Pressure Vessel Project is the desire to link the AM process variables to the final performance of the component (or the product), which leads to informed decisions on how to tweak the process in order to make a better product.
In the world of science, form is related to function. For example, a fish is equipped with fins to help it swim, and lung cells are quite thin to allow gas transfer for breathing. On

any scale, form couples with function. In a pressure vessel, its form on a microscale is coupled with its function (performance).

The pressure vessel's microstructure is predictive of certain properties, such as strength and toughness. So, when Sigma scientists and engineers identify a specific microstructure (called characterizing) in a pressure vessel, they are able to associate a list of predictable properties that go with it. They can tweak the process variables in order to tweak the microstructure, which results in a change in performance. This is science-based qualification, and it gives the scientists greater control over the product. Science-based qualification is not a guess-and-check process; rather, it is a fundamentally different way of qualifying components. By linking structure to properties, a component can be qualified based on whether it has the right microstructure, regardless of the synthesis or production route.

However, AM is a unique form of manufacturing and produces microstructures that are considerably different from what would be seen if casting or forming methods were used. Everything scientists know about how microstructure from those latter methods relates to performance must be tossed out when considering AM, and new form-function links must be forged. “This necessitates creating new linkages between microstructure and properties,” Carpenter says, “and this is one of the reasons this project is so important.”

Sigma: a manufacturing powerhouse

The Sigma Complex was the obvious choice to headquarter the Pressure Vessel Project because Sigma houses many of the world's top manufacturing and metallurgical scientists under one roof. Working elbow-to-elbow, these experts can put their heads together at a moment's notice and offer instant feedback on the project.

Carpenter took advantage of this perk when one of the machines used in the Pressure Vessel Project went down. Between the resources at Sigma (both people and equipment) and the rapid learning from science-based qualification, Carpenter's team was able to continue to make headway. “We did have machines go down over the course of the project,” Carpenter explains. “Our efforts in science-based qualification smoothed over this speedbump rather than causing us to start over.”

A substitute for the downed machine was put in place and produced quality pressure vessels. This highlights the importance of science-based qualification—understanding why a process works and how it produces a component with specific performance characteristics unchains the scientists from having to always replicate the same process on the same machines. In real life, things break while deadlines still loom. Carpenter's team members showed their newly learned links between microstructure and properties allowed them to change their process while still producing a pressure vessel of predictable performance. The applications of this strategy are far-reaching.

Jumping on the bandwagon

Scientists and engineers at Sandia, Savannah River, Lawrence Livermore, and Kansas City collaborate with the folks at Los Alamos on the Pressure Vessel Project. It is clear there is more to this project than meets the eye; the applications of AM and the science-based qualification process entice researchers from all walks of life.

With this level of inter-laboratory collaboration came the need for a biannual technical exchange, so everyone can be kept up to speed and contribute to the project in a timely and useful manner. Twice a year, everyone gathers in one location to hash out the latest data and analyses and contribute their ideas for reaching the NNSA objectives.

Altogether, there are seven deliverable categories for the AM project: vessel design, a qualification plan, AM building, material and processing assurance, modeling and simulation, inspection and metrology, and characterization/performance/function testing.

These categories are discussed both independently and as they relate to each other. For instance, the vessel design and AM building teams ensure that what is designed is buildable and what is buildable will meet the prescribed requirements.
The five institutions will continue to collaborate as the Pressure Vessel Project reaches a critical turning point—a change in focus from meeting NNSA performance objectives to scaling up and perfecting the process in order to build other components.

The future of AM

Three years of hard work have led to the successful data on Carpenter's computer screen (which proves the NNSA objectives have been met), but the Pressure Vessel Project is far from complete. Now that the initial process has been determined through science-based qualification, the next phase of the project will focus on scaling up and transitioning AM to programs.

All eyes will be on the technology readiness level (TRL), a numerical estimation of the technology's maturity. The scale is from 1 to 9, with 9 being the most mature. The pressure vessel is considered to be at a TRL level of 3 right now, with the hopes that it will be at a TRL level of 5 by the year 2020. Most programs require a TRL level of 5 (along with a possible pathway to TRL level of 9) before adopting a process.

Thanks to the science-based qualification method, the scale-up for AM is expected to be straightforward, as compared to more traditional manufacturing techniques. Scale-up inherently causes changes in a manufacturing process, which can cause unexpected problems, but Carpenter is already well-versed in overcoming these challenges.

Carpenter and his team view the future of AM as very bright, with many collaborations expected in the coming years. Innovations in the AM materials used, the components produced, and streamlining the process as well as the characterization are all anticipated. Along with powder-bed AM, other types of AM will be investigated, and modeling and simulation tools will be developed to further enable science-based qualification.

Not only is the Pressure Vessel Project pertinent to national security, particularly as it relates to the aging stockpile, but AM is also predicted to replace older, less-efficient manufacturing techniques. AM is expected to be a "greener," more sustainable technique that will reduce the production footprint as well as the cost of fabrication within the NNSA plants (as compared to other manufacturing methods).

Carpenter's team is cognizant of its position on the frontlines of AM development. "We're in an exciting area," Montgomery says, "we're seeing the innovation take place." His team is also aware that staying ahead of AM innovations is important for national security, as other countries are beginning to adopt this technology. No others, however, are as adept at science-based qualification as the researchers at Sigma and their collaborators at the four other national laboratories.

1350 Central Avenue
Los Alamos, NM 87545

BRADBURY SCIENCE museum

(505) 667-4444
www.lanl.gov/museum

Managed by Triad National Security, LLC for the U.S. Dept. of Energy's NNSA |
© Copyright Triad National Security, LLC. All Rights Reserved.